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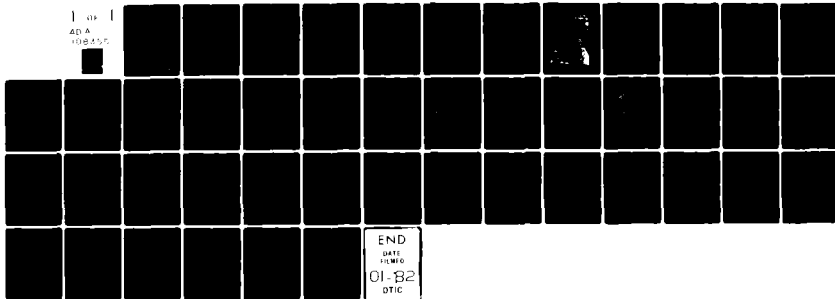
VANDERBILT UNIV NASHVILLE TN DEPT OF PSYCHOLOGY  
THE PRIMACY OF DEPTH IN VISUAL PERCEPTION. (U)  
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The Primacy of Depth  
in Visual Perception

Robert Fox

Department of Psychology  
Vanderbilt University  
Nashville, Tennessee 37240

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November 1981

Technical Report

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Prepared for:

Engineering Psychology Programs  
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### Erratum

There are errors in the description of the results of two of the experiments on the perception of biological motion by infants that are discussed on pages 27 and 32 and depicted in Figures 19 and 20. The correct description is given below.

The data given in Figure 19 are (contrary to the legend) for the experiment that employed the motion of hands as a target. In that experiment, only the performance of the 6-month-old group reached significance.

The data given in Figure 20 are (contrary to the legend) for the experiment that employed the upright runner as a target and the inverted runner as a foil. In that experiment the performance of both the 4-month-old and 6-month-old group was significant; in the figure an asterisk indicating significance is missing from the 4-month-old group.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)  This report is a slightly edited version of an invited address (New Fellows Address) given by the writer at the national convention of the American Psychological Association in Los Angeles on August 28, 1981. The implications of several kinds of recent investigations of three- dimensional visual space perception are discussed, including investi- gations performed by the writer and his colleagues, and summarized in		

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Final Report N14-1101 81C-0003, Contour Interaction in Visual Space.

The results of all investigations are interpreted as supporting the claim that the X Y Z position of objects in visual space is processed quite early by the visual system. This initial identification of the loci of objects in space serves to control subsequent analysis of the characteristics of those objects. This interpretation supports a general theory of visual space perception that assumes there is an internal, continuous representation of visual space within the visual system. This representation is assumed to be an intrinsic hard-wired characteristic of that system. Conversely, support is not given to an alternative general theory of space perception that assumes depth information is processed relatively late in the visual system by an analysis of specific cues to distances, cues which acquire their significance gradually by repeated exposure to the environment.

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### The Primacy of Depth in Visual Perception

As a new fully fledged Fellow of APA I am going to indulge myself by making a strong claim that goes beyond the data that can support it. So, be aware that this is more an exercise in theoretical speculation than an empirical report.

The claim I want to advance is that the first step in processing visual information is the determination of where in space stimuli or objects are located. That is, X, Y, and Z values are given first--only after that is the content of stimuli determined.

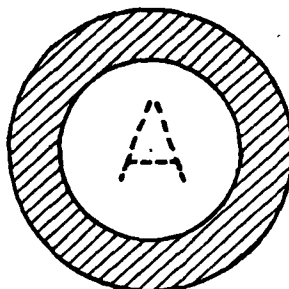
Now one reason for making that claim comes from the experimental answer to the question, "Would interactions among spatially adjacent stimuli still occur if the interacting elements were displaced in different depth planes, that is, had different Z-axis values"? Interactions here refer to a whole range of phenomena characterized by a change in the perceived attributes of a stimulus that is induced by the contextual stimuli within which it is embedded. Some familiar examples are illustrated in the following two figures. In Figure 1, the conditions of metacontrast masking are illustrated. The masking annulus reduces the perceptibility of the test stimulus. And in Figure 2, the change in the apparent length of the horizontal lines induced by their placement within the arms of an acute angle, the so-called Ponzo illusion, is illustrated. Would the changes typified by these phenomena still occur if the critical elements were in different depth planes? That question is inspired by the different answers it would receive depending upon which of two very general views of space perception is correct.



TEST ALONE

A

TEST PLUS MASK



METACONTRAST MASKING

Figure 1. Stimulus configuration used to demonstrate metacontrast masking.

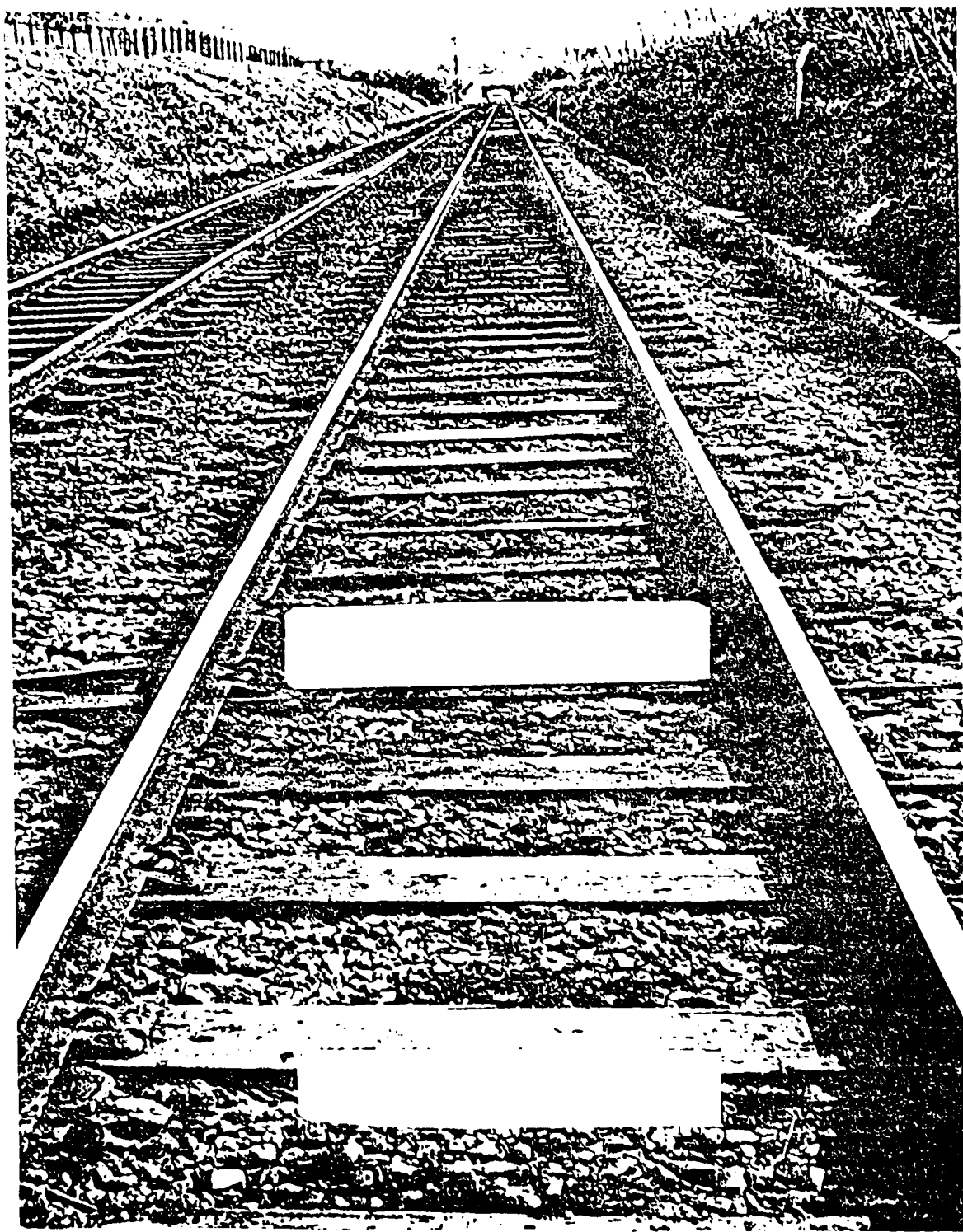


Figure 2. The Ponzo configuration embedded within a context of enhanced linear perspective.

One view, which can be called cue theory, assumes that perception of space is constructed from an analysis of the cues conveyed by the objects that populate the space. This requires that information about the attributes of objects be extracted first, prior to a determination of their position in space. This formulation, which can readily be traced to Wundt, has been widely accepted, both in the form of explicit theory and as an implicit assumption--as for example, in the lists of cues to depth. Note that models of interactive phenomena such as simultaneous contrast that are based on the concept of lateral inhibition make no provision for depth or Z-axis separation. From the standpoint of cue theory it seems clear that depth separation would have no effect on interaction so long as the conditions of proximal stimulation remained constant.

The opposite prediction is made by the alternative view of space perception, which may be called relational theory in deference to its central role within the Gestalt tradition. This view assumes that the positions of objects in space are immediately given by an internal representation that registers and preserves information about spatial position. On relational theory depth separation would alter interactions between stimuli by effectively changing the distance between them.

Experiments that test these contrasting predictions are relatively small in number because it is technically difficult to produce changes in depth without introducing confounding changes in proximal stimulation. Nevertheless, some experiments have been implemented successfully, and I am now going to describe several examples. In this regard the research program of Walter Gogel is particularly noteworthy. In his effort to develop a general theory of space perception he has formulated an

hypothesis known as the "Adjacency principle", which asserts, in effect, that the interaction among objects in visual space is an inverse function of the Euclidian distance between them. To that end, he has devised tricks for producing changes in apparent depth. To cite one example, (Gogel and Newton, 1975) he manipulated various depth cues to induce an apparent depth separation between the rod and the frame in a standard rod and frame test situation. Figure 3 shows the general stimulus situation. When both rod and frame were in the same depth plane the tilted frame produced the expected tilt of the rod. But when the rod and frame appeared in different depth planes and the rod appeared to be closer to the observer than the frame, the effect of the frame was significantly reduced.

Working within a theoretical framework different from Gogel's, Allan Gilchrist (1980) has produced a striking demonstration of the effect of apparent depth on the perception of lightness. Gilchrist's basic experimental situation is illustrated in Figure 4.

It is well known that the ratio of the proportion of light reflected from adjacent surfaces will determine whether a particular surface is seen as white, gray, or black. Gilchrist introduced to this ratio-relationship differences in the apparent depths of the surfaces. As shown in the figure the depth cue of interposition is used to vary the depth position of the target--it can either appear at the far wall in the plane of the much brighter surface or at a nearer position in the plane of the much dimmer surface. For both positions the proximal stimulation remains essentially the same. But the change in depth position produced a large change in the apparent whiteness of the target, which

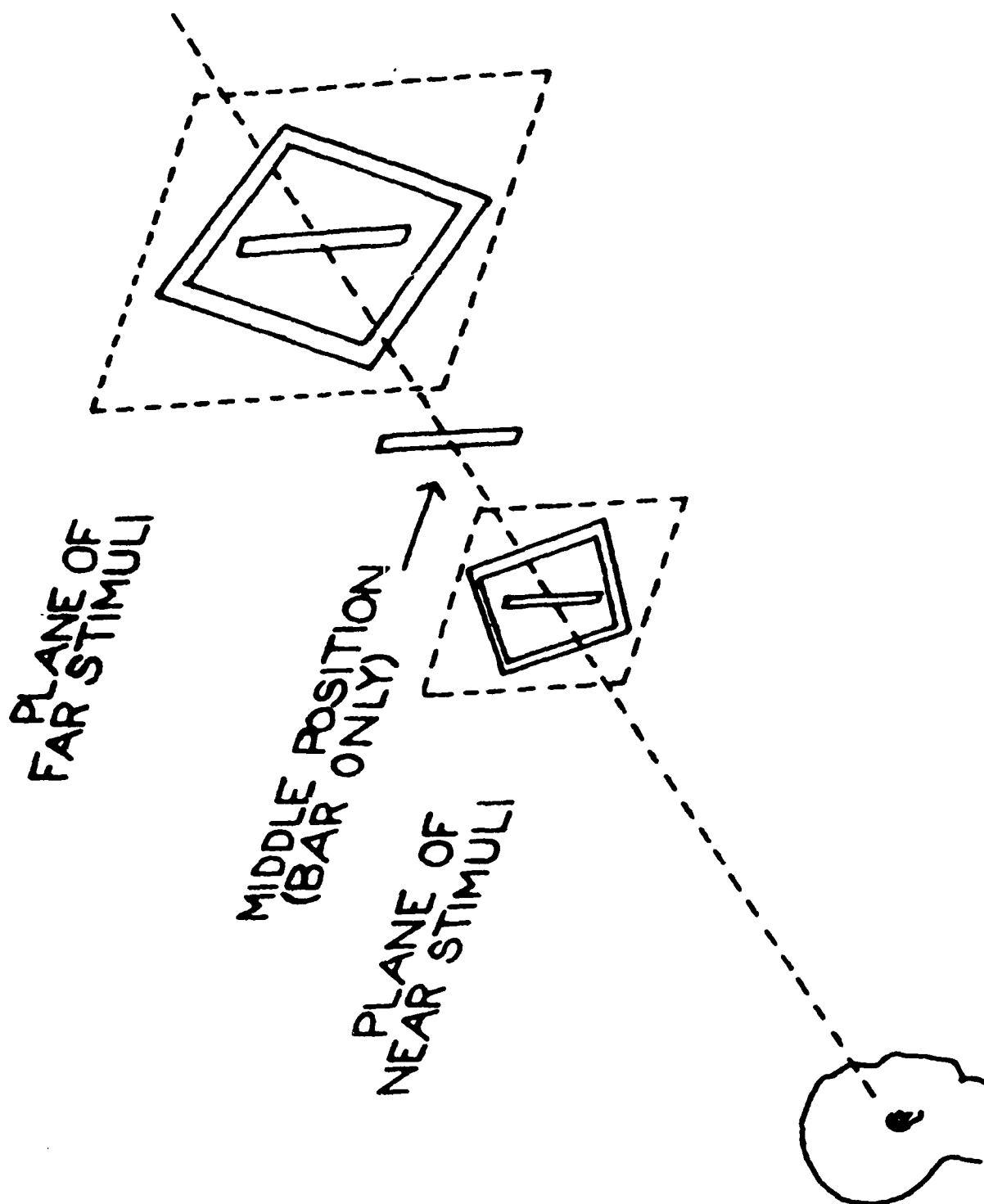


Figure 3. Displacement in depth of the rod relative to the frame  
(from Gogel & Newton, 1975).

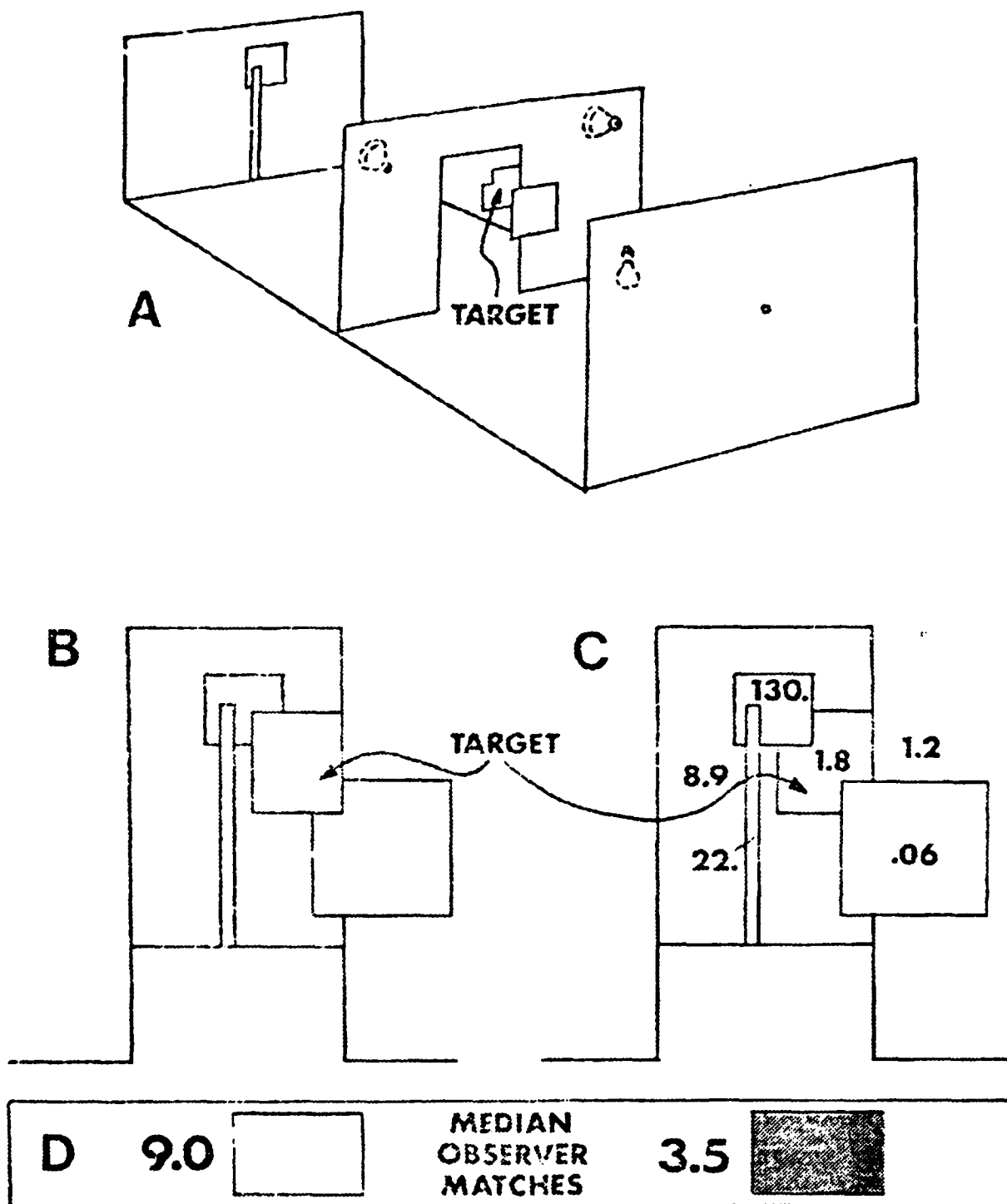


Figure 4. (A) View of stimulus display. (B) The display in which the target appeared in the rear plane. (C) The display in which the target appeared in the far plane. (D) Average match from a Munsell chart for the two displays (from Gilchrist, 1980).

is indicated in the panel at the bottom of the slide. When seen against the dimmer surface at the near position the target appears quite white, with a Munsell value of 9 on a 10-point scale; when seen against a brighter surface at the far position it appears much dimmer with a Munsell value of 3.5. Such a result indicates that apparent depth plays a much more significant role in determining the percent than does the ratio of luminances between the surfaces that impinges upon the retina.

But as I said earlier, experiments on the effects of depth separation are difficult to implement because apparent depth must be induced in a convincing way without at the same time introducing confounding changes in proximal stimulation. This has placed a limit on the kinds of perceptual interactions that can be examined and on the magnitude of the variables that can be manipulated. For example, in the Gilchrist situation (1980) it is not possible to systematically vary the depth position of the target over a series of depth positions.

These considerations motivated my colleagues and me to develop a more flexible method for pursuing the question of the effect of depth on stimulus interactions. The approach we have taken capitalizes on the by-now well-known random element stereogram, a version of which is illustrated in Figure 5. Random element stereograms, which were developed by Julesz in 1960, consist of large arrays of randomly ordered dots or elements. As you can see, neither the left-eye view nor the right-eye view contain any recognizable shape or contour. But retinal disparity that induces stereoscopic depth perception can be introduced by displacing a subset of elements within a matrix viewed by one eye. This displacement is camouflaged, however, by the myriad of surrounding dots and cannot be

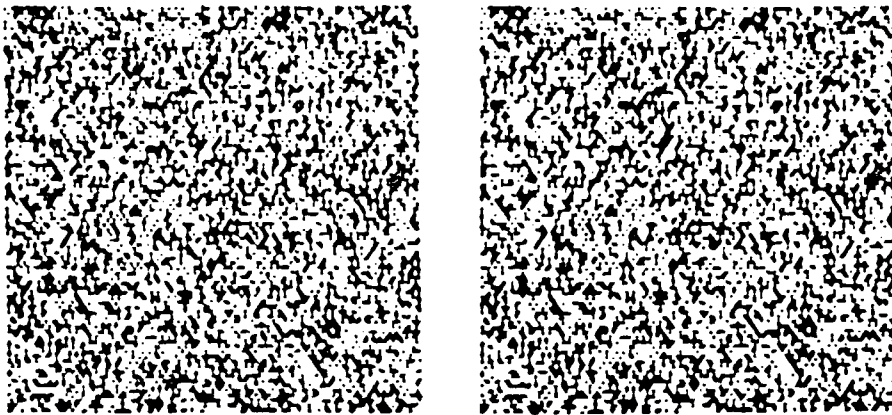


Figure 5. The two monocular patterns of a typical static random-element stereogram. When each pattern stimulates a separate eye, a stereoscopic form can be perceived (after Julesz, 1971).



seen. But when an observer with stereopsis views the left- and right-eye images, the disparity is detected by the binocular visual system and this results in the perception of a palpable clear-cut stereoscopic form standing out in depth. These forms arise from some central stage of the visual system where inputs from both eyes are combined and, in that sense, do not engage the retina or other peripheral stages. Nevertheless, the stereoscopic or cyclopean contours have been shown to possess many of the functional characteristics of physical contours. That is, they can induce aftereffects, eye movements, and interact in much the same manner as their physical counterparts. Our approach then has been to replicate or reproduce the interactions among physical stimuli in stereoscopic space with stereoscopic stimuli. This allows apparent depth to be changed very easily and eliminates entirely the meddlesome problem of confounding changes in proximal stimulation. Our efforts have been greatly aided by the development of a flexible system for generating, in real time, dynamic random element stereograms. This system is illustrated in Figure 6. The display device is a modified color TV receiver upon which thousands of red and green dots are continuously generated many times a second. When an observer views the display with appropriate red and green filters before the eyes, the red and green dots are physically segregated to separate eyes, thereby fulfilling the conditions of stereoscopic viewing. This, of course, is the well-known anaglyph method of stereoscopic presentation. All parameters of the stereoscopic display are controlled by a hardwired electronic unit composed of integrated circuit. The devices marked "Optical Scanner" consist of modified TV cameras that operate as flying-spot scanners.

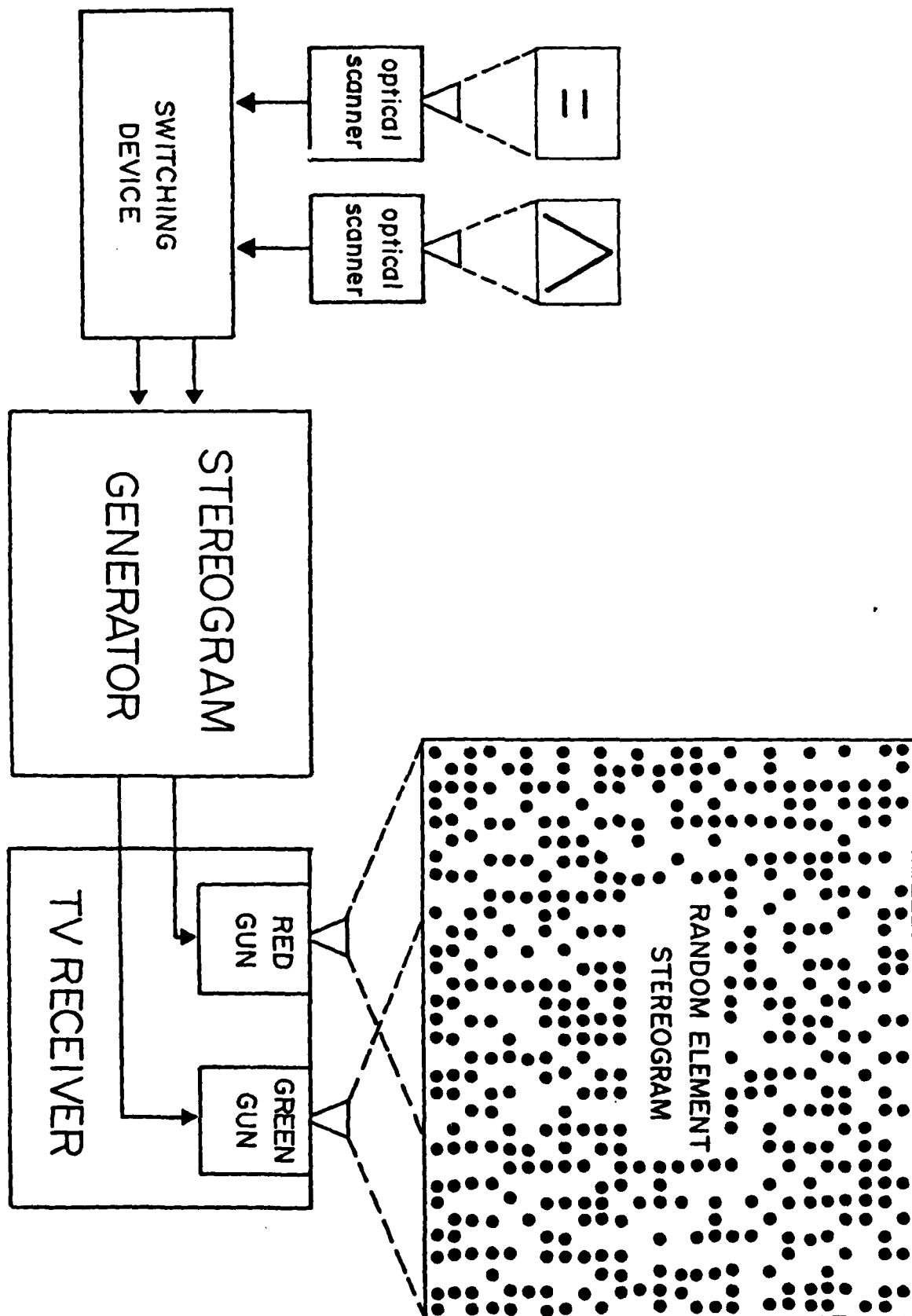


Figure 6. Display, programming, and logic units of the stereogram generation system. 11

Any two-dimensional achromatic form that is seen or scanned by the cameras is immediately converted into its stereoscopic equivalent. Even quite complex shapes undergoing continuous motion can be presented as stereoscopic or cyclopean configurations. This system was developed initially to test for the presence of stereopsis in animals and young infants. Yet it also lends itself to the pursuit of more cognitive questions.

And one of the first questions that Steve Lehmkuhle and I posed was whether depth position would influence the well-known and well-investigated phenomenon of metacontrast masking. The elements of our masking display are illustrated in Figure 7. The test stimulus is a stereoscopic form configured as a Landolt C, whose gap position could be randomly varied over trials to be at four clock positions--12, 3, 6, and 9. Observers were required to make forced-choice judgments as to the gap position. The mask is a stereoscopic form configured as an annulus whose inner contour was spatially adjacent but not overlapping with the outer contour of the Landolt C target. Without the mask, thresholds were set individually for each observer so that they achieved a stable level of recognition performance of 80%. At that performance level, the duration of exposure of the Landolt C ranged from 48 to 62 msec. In a series of experiments we have found that masking in this situation resembles, in many ways, the masking found with physical contours, so long as the annulus and the target are in the same depth plane. But, as Figure 8 depicts schematically, our main concern was the effect of changing the relative depth position of target and mask. Figure 9 shows the effect of increasing depth separation on masking when the annulus is displaced in depth so that the test stimulus appears to be in a depth plane closer to the observer.

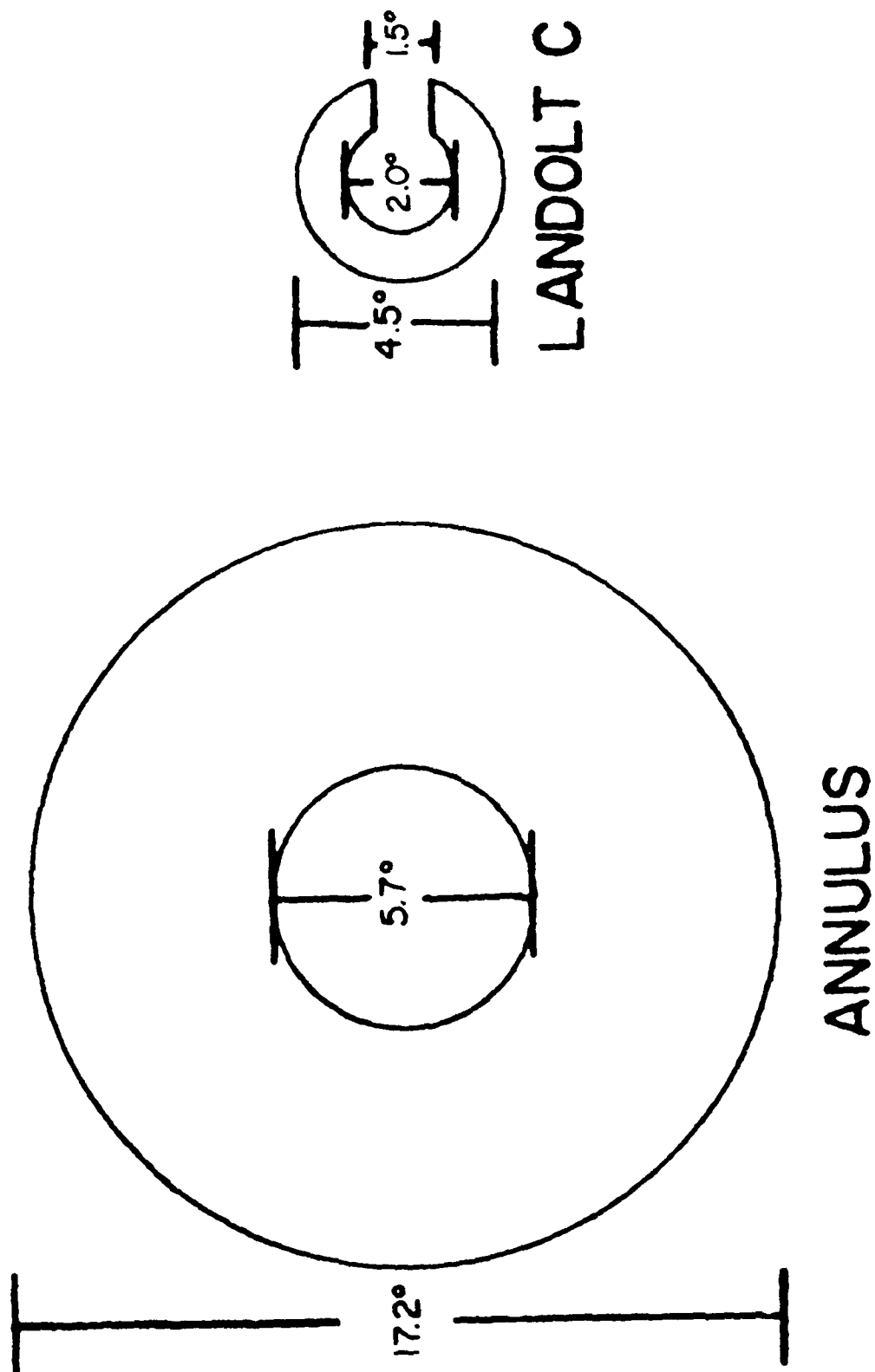


Figure 7. Configuration and dimensions of stereoscopic stimuli employed in experiments on metacontrast masking (from Lehmkuhle & Fox, 1980).

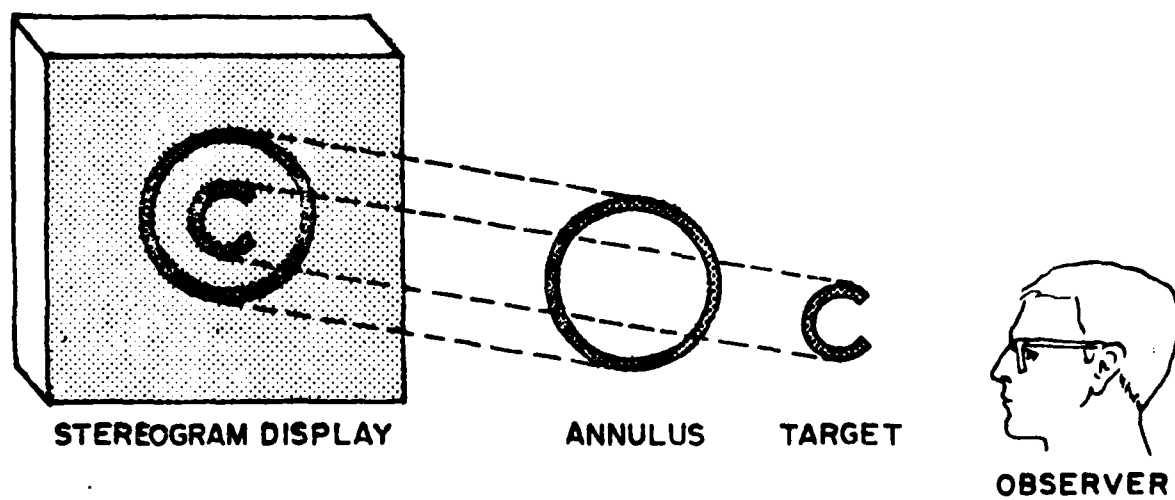


Figure 8. Stimulus arrangement showing relative depth of target (in front) and annulus.

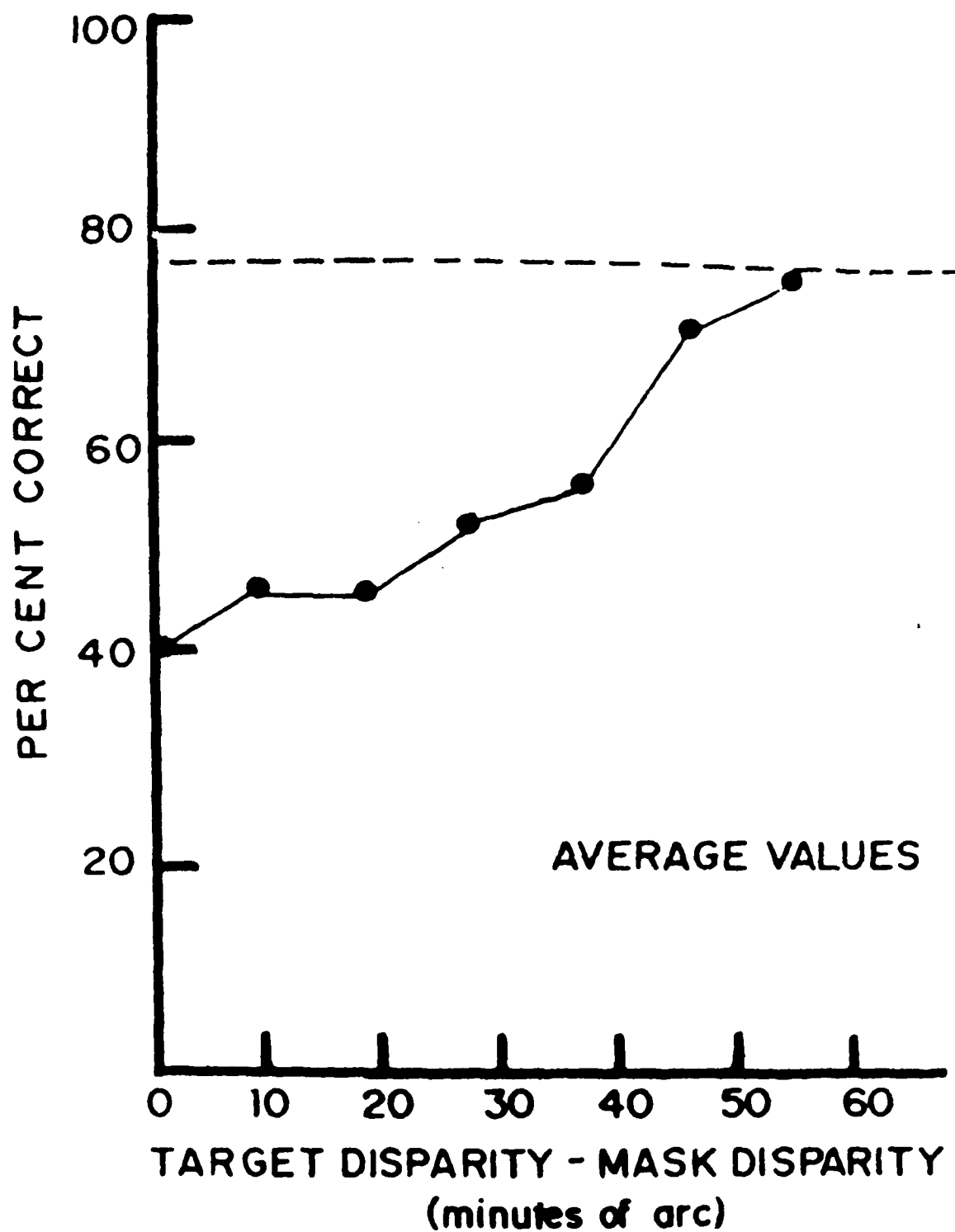


Figure 9. Detectability of test as a function of the separation in depth of test and mask (from Lehmkuhle & Fox, 1980).

When both test and mask occupy the same depth plane considerable masking occurs, on the order of a 40% reduction in recognition performance. But with increasing values of depth separation, there is a monotonic decrease in the amount of masking, and finally, recognition performance climbs to the baseline level. The most reasonable interpretation of these data is that masking requires the same depth positions for both test and mask.

This dependence on depth position is not restricted, however, to the threshold level destructive interference of the kind typified by visual masking. We have also found it at the suprathreshold level with what might be called distortive interactions as represented by the geometric visual illusions such as the Ponzo illusion. Using our stereogram generation method, Bob Patterson and I presented the Ponzo illusion in the form of stereoscopic contours. The general arrangement is illustrated in Figure 10. We measured illusion magnitude as a function of displacements in depth of the inducing angle (see Figure 11). The results are shown in Figure 12. When the test lines are in different depth planes and in front of the inducing angle the illusion magnitude decreases monotonically as the difference in depth increases. Note also that when the test lines are in a depth plane behind the inducing angle there is some tendency for illusion magnitude to increase. We have noticed the asymmetry in other experiments including those on masking and have dubbed it the "front effect" in deference to the hypothesis that the visual system may have some positive bias for a stimulus that is in front of another and closer to the observer. The front effect may be related to the dominance of figure over ground and is an interesting phenomenon in its own right. But for the purpose of showing that depth position is important,

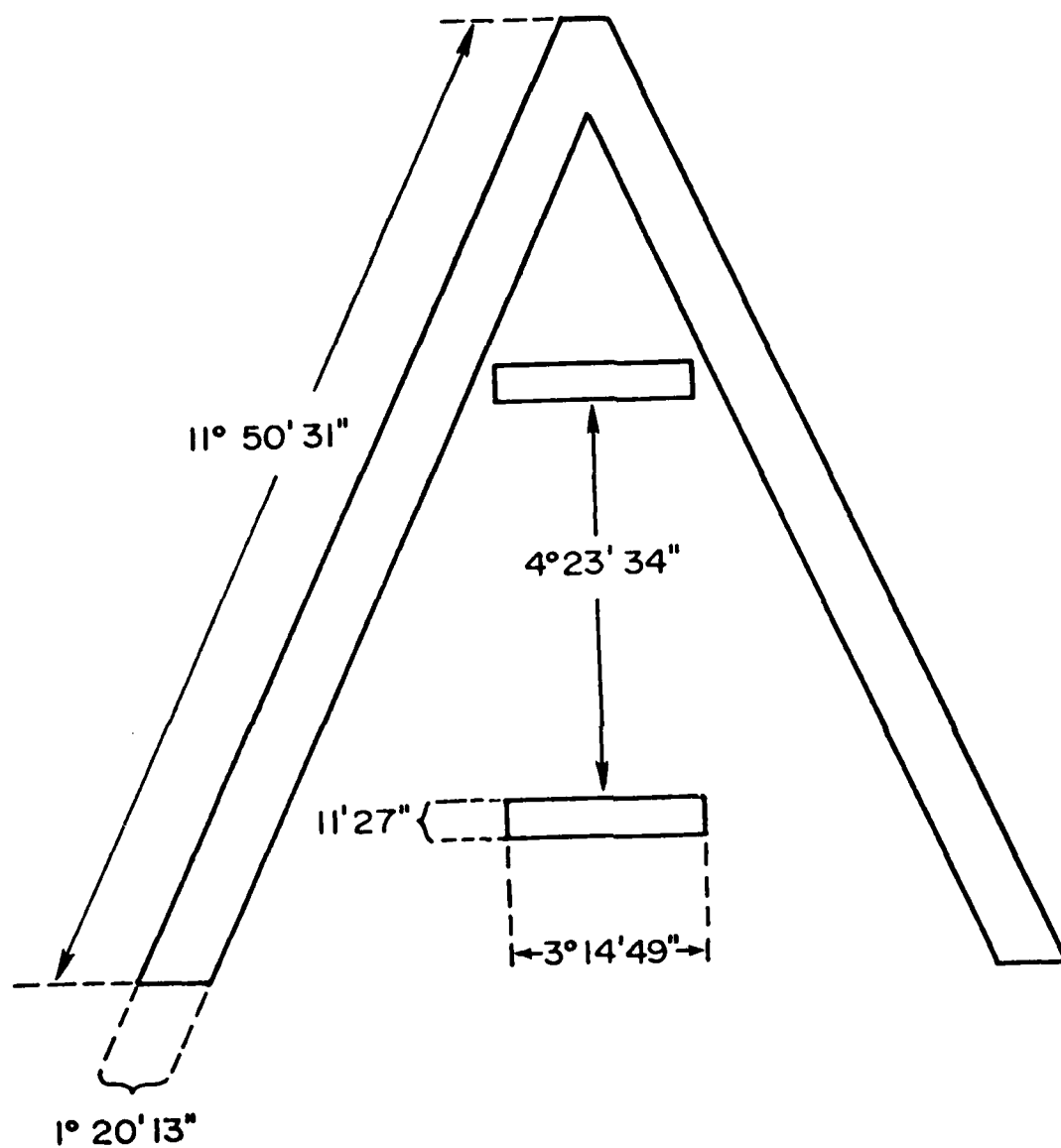


Figure 10. Configuration and dimensions of stereoscopic stimuli employed in the experiment on the Ponzo illusion (from Fox & Patterson, 1981).



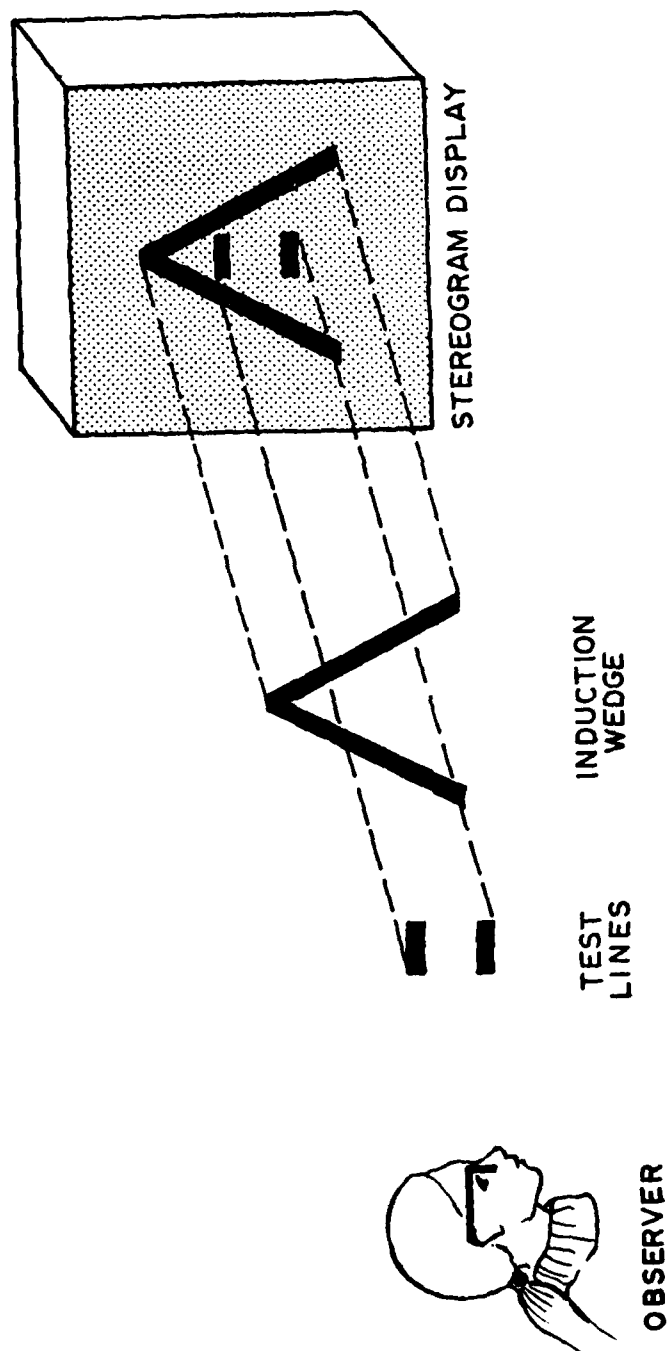


Figure 11. Stimulus arrangement showing relative depth of test lines (in front) and inducing angle. Note that the term "inducing angle" is synonymous with induction wedge in the figure (from Fox & Patterson, 1981).

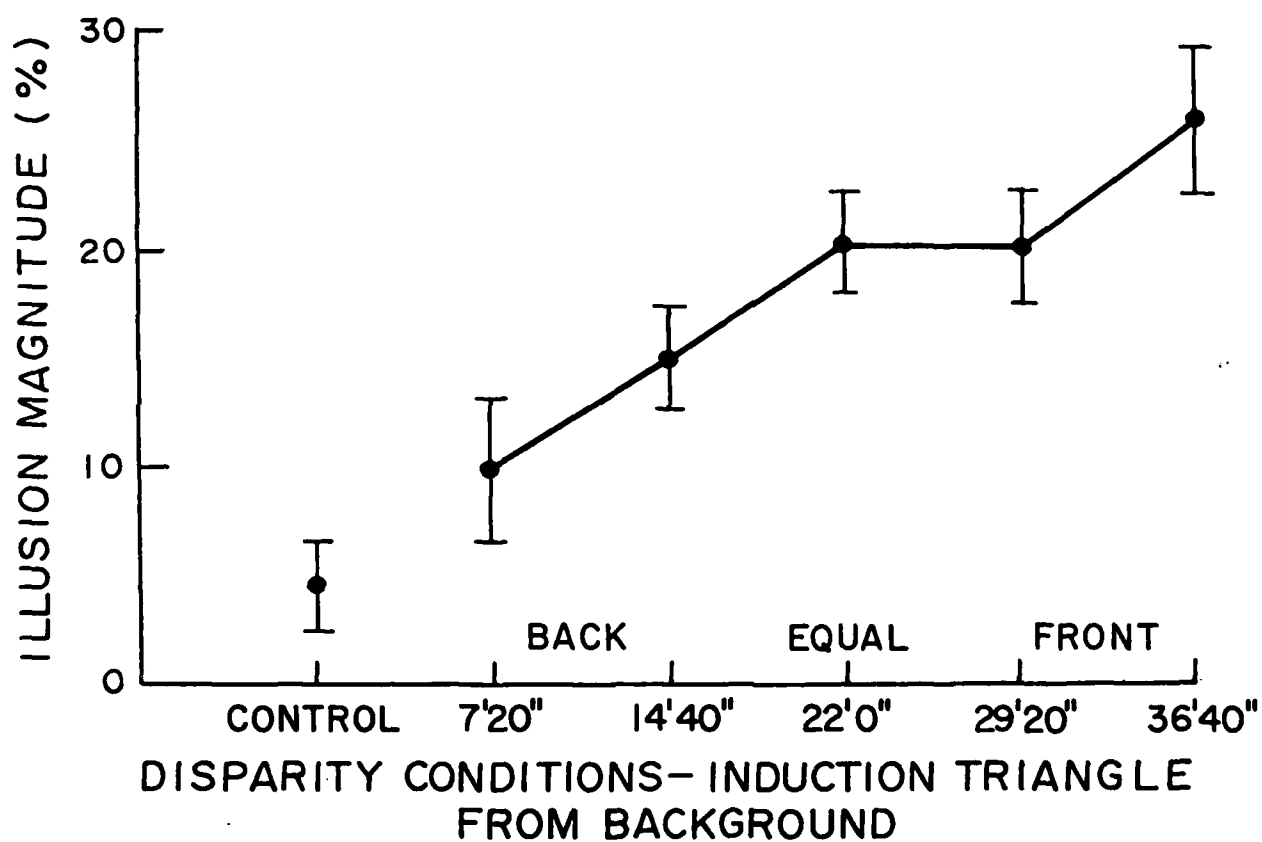


Figure 12. Illusion magnitude as a function of the separation in depth of test lines and inducing angle (from Fox & Patterson, 1981).

it need not concern us here.

Let's consider now the effect of depth on a phenomenon that does not seem to involve interactions per se but rather such processes as adaptation and aftereffects. Steve Lehmkuhle and I have been able to generate an array of stereoscopic vertical contours that appear continuously and move in one direction. Such an array of contours is indicated schematically in Figure 13. To produce this array of moving stereoscopic contours we simply had our optical scanner look at an array of achromatic contours continuously moving on an endless belt. We had observers attend to the moving stereoscopic or cyclopean contours for some seconds and then we stopped the movement. With movement stopped the observers perceived an apparent motion of the stationary contours in the opposite direction. Or in other words, we produced a stereoscopic form of the waterfall illusion or motion aftereffect. The duration of the aftereffect ranged from 8 to 14 seconds. We then determined the effect of displacing the stationary contours in depth on the strength of the aftereffect. The results are shown in Figure 14. At the zero-disparity position both the moving and the stationary contours are in the same depth plane. But in the conditions marked +30 and -30 the stationary contours are displaced forward and backwards from the moving contours. These displacements result in a significant reduction in the strength of the aftereffect. Thus these data also suggest that depth position is a significant factor in the induction of adaptation phenomena.

All of the experiments I have discussed here, plus others that I did not mention, all show the strong effects of depth position and support the view that a common depth position is a necessary pre-condition for

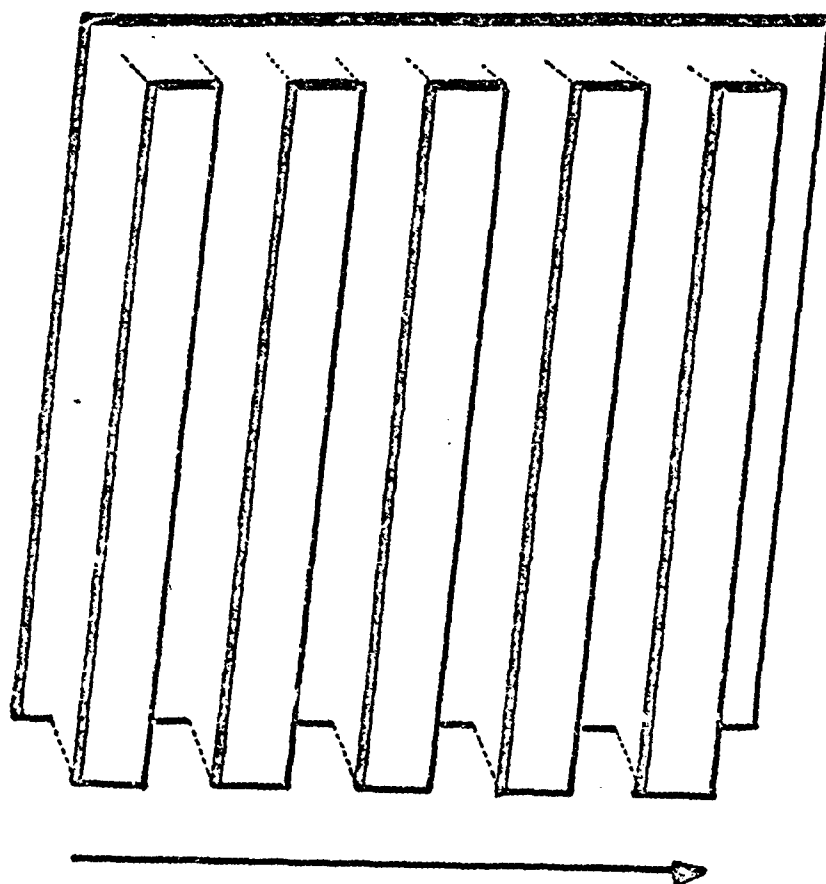


Figure 13. Configuration of moving stereoscopic contours employed in experiment on the motion aftereffect (from Lehmkuhle & Fox, 1977).

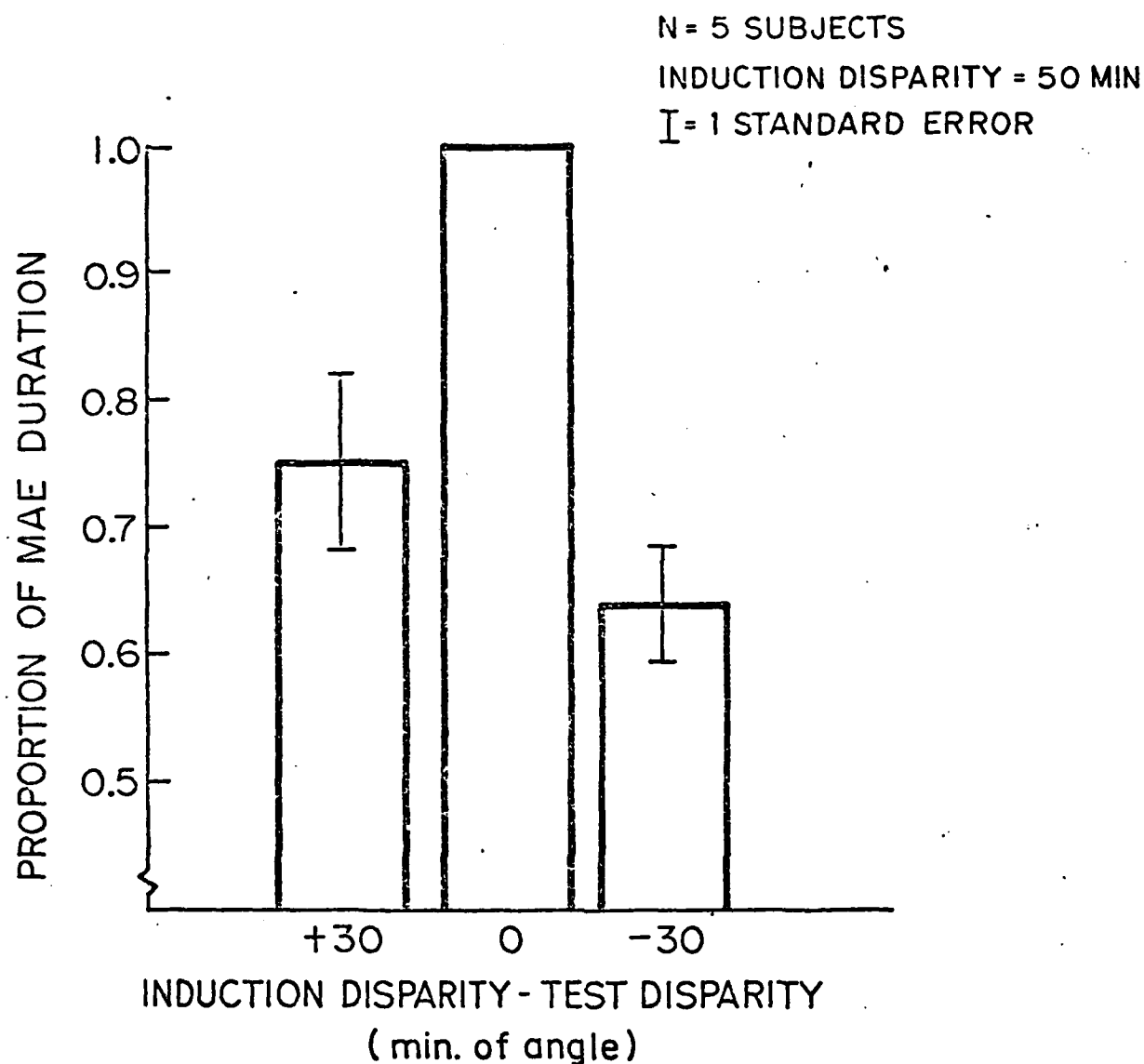


Figure 14. Proportion of motion aftereffect duration as a function of the separation in depth of the stationary (test) contours and the moving (induction) contours (from Lehmkuhle & Fox, 1977).

the wide range of visual phenomena that have been examined. This outcome is fully consistent with the idea that the depth positions of objects in space are encoded or represented in three dimensions in agreement with the relational theory of visual space perception. And that is one reason I made that claim at the beginning of this talk.

Now a second reason comes from a quite different set of data on the development of visual perception in human infants.

As many of you know, research on the sensory and perceptual capacities of infants is proceeding at a great pace. This is due, in part, to the development of new methodologies that permit the application of sophisticated psychophysical techniques to the testing of perceptual capacities in infants. The general result, from a variety of studies, is that infants have much more elaborate and refined perceptual abilities than previously thought.

For instance, Dick Aslin, Sandy Shea, and I have investigated the development of stereoscopic depth perception in infants. As a testing device we used random element stereoscopic contours that appear to move about in stereoscopic space so as to attract the infants' visual attention. To provide an objective index of the infants' visual preference we used the technique known as the forced-choice preferential looking method which has been developed by Davida Teller and colleagues (Peeples & Teller, 1975). And we have found that stereopsis becomes manifest in most infants at around  $3\frac{1}{2}$  to 4 months of age (Fox, Aslin, Shea, & Dumais, 1980).

More recently Cynthia McDaniel and I have been investigating the ability of infants to perceive the structure inherent in moving patterns

of dots that represent biological motion. Biological motion, as that concept has been developed by Gunnar Johansson (1978), refers to the characteristic pattern of movements made by humans and animals as they locomote in the environment. Johansson discovered that this pattern can be conveyed by a small number of dots or points of light attached to the joints of the moving creature. When motionless the points of light, say 10, appear as a meaningless jumble but as soon as motion begins, adult observers immediately perceive the underlying structure. That is, one correctly perceives, for example, a human as walking or running or dancing. This means, according to Johansson, that observers are sensitive to the invariant information that is conveyed by the relationship among the moving points of light. This view is very similar to James Gibson's (1950) hypothesis that perception is immediately given by the information inherent in the optical array. Johansson and Gibson consider that sensitivity to biological motion is an intrinsic or hardwired capacity of the visual system that does not require experience for its manifestation.

In addition, and the main point for us, is that biological motion is inherently three-dimensional. The correct perception of the human or animal represented by the moving points of light implies that the observer can process information in three dimensions.

Since infants are sensitive to stereoscopic depth information by 4 months of age, it seemed natural to determine if they are also sensitive to the more complex three-dimensional information intrinsic to biological motion. Our general approach was to use the preferential looking method in which a display containing a biological motion pattern is paired with a foil display containing a meaningless motion pattern. It is assumed that if the

infant is sensitive to biological motion it will prefer to spend more time looking at the meaningful, presumably more interesting motion pattern rather than at the meaningless alternative. To provide an objective index of the visual preferences of infants we used the forced-choice version of the preferential looking method. The logic of this method directly follows the logic of the forced-choice response method used in contemporary psychophysics. The motion pattern, which is analogous to a target or signal, is paired with the meaningless pattern, which is analogous to noise or no signal, with both presented simultaneously over a series of trials. The left-right positions of the target and the noise are randomly interchanged with the restriction of equal occurrence on each side. An observer who is unaware of target position on each trial is required to make a forced-choice judgment of the location of the target, left or right, based on information gleaned from observing the infant. If the observer scores significantly above chance this implies that the infant was engaged in some behavior systematically related to the position of the target, as for example, turning its head and eyes to follow the target's position. By focusing on the observer's performance the method eliminates the inherent subjectivity associated with judgments of where at any given time an infant is looking.

Figure 15 depicts one of the biological motion patterns that we used. When the dots were in motion adult observers immediately perceived the pattern as a human running in place. This pattern was paired with two different foils in two separate experiments. In one case the foil consisted of ten dots, each moving in a quasi-random fashion independent of the other dots. To adult observers this appeared quite different from



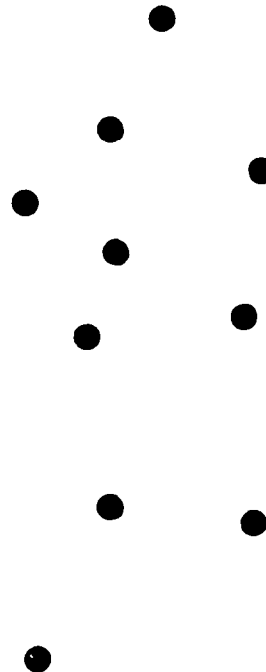
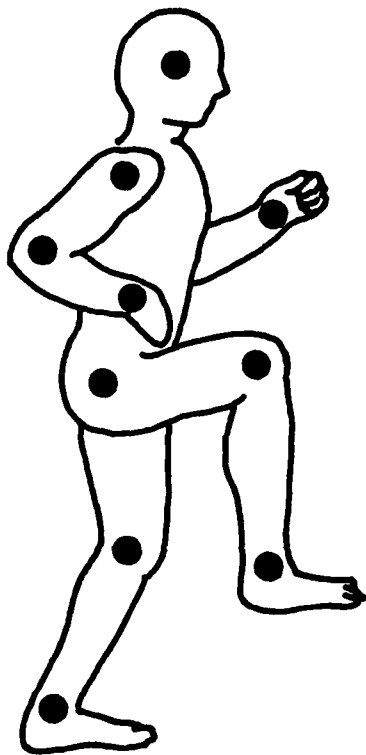


Figure 15. Stimulus configuration used to convey perception of a human running in place.

the person running in place. A second foil was the running figure turned upside down, a manipulation which impaired perception of the pattern as a running figure, yet appeared more similar to the runner than dots simply moving in random directions. In a third experiment a second biological motion stimulus was used consisting of 26 dots representing a pair of hands coming together and engaging in a collaborative rotary motion. The foil in this case consisted of the same number of dots placed on parts of the hands that conveyed less information about hand motions. In this case the difference between target and foil was much less clear-cut for adult observers.

Figure 16 shows the general testing situation as seen by the infant. Target and foil are viewed side by side on small television monitors in front of which the infant and parent are seated. Figure 17 gives a side view. The observer, concealed from the infant's view, views the infant through a peephole while a second experimenter switches the position of target and foil in accord with a predetermined schedule. Each trial takes about 10 seconds and 20 to 40 trials are typically obtained.

Figure 18 shows the results of a cross-sectional study using three groups of infants, ages 2, 4 and 6 months, in which the target was the running person and the foil consisted of the random motion of the dots. No significant preference was found for the 2-month-old infants, yet both the 4-month-old and 6-month-old infants displayed a significant preference for the running figure.

In Figure 19 the results of a second cross-sectional study are shown in which the target was again a running figure and the foil was the running figure shown upside down. The 4-month-old infants did not differ

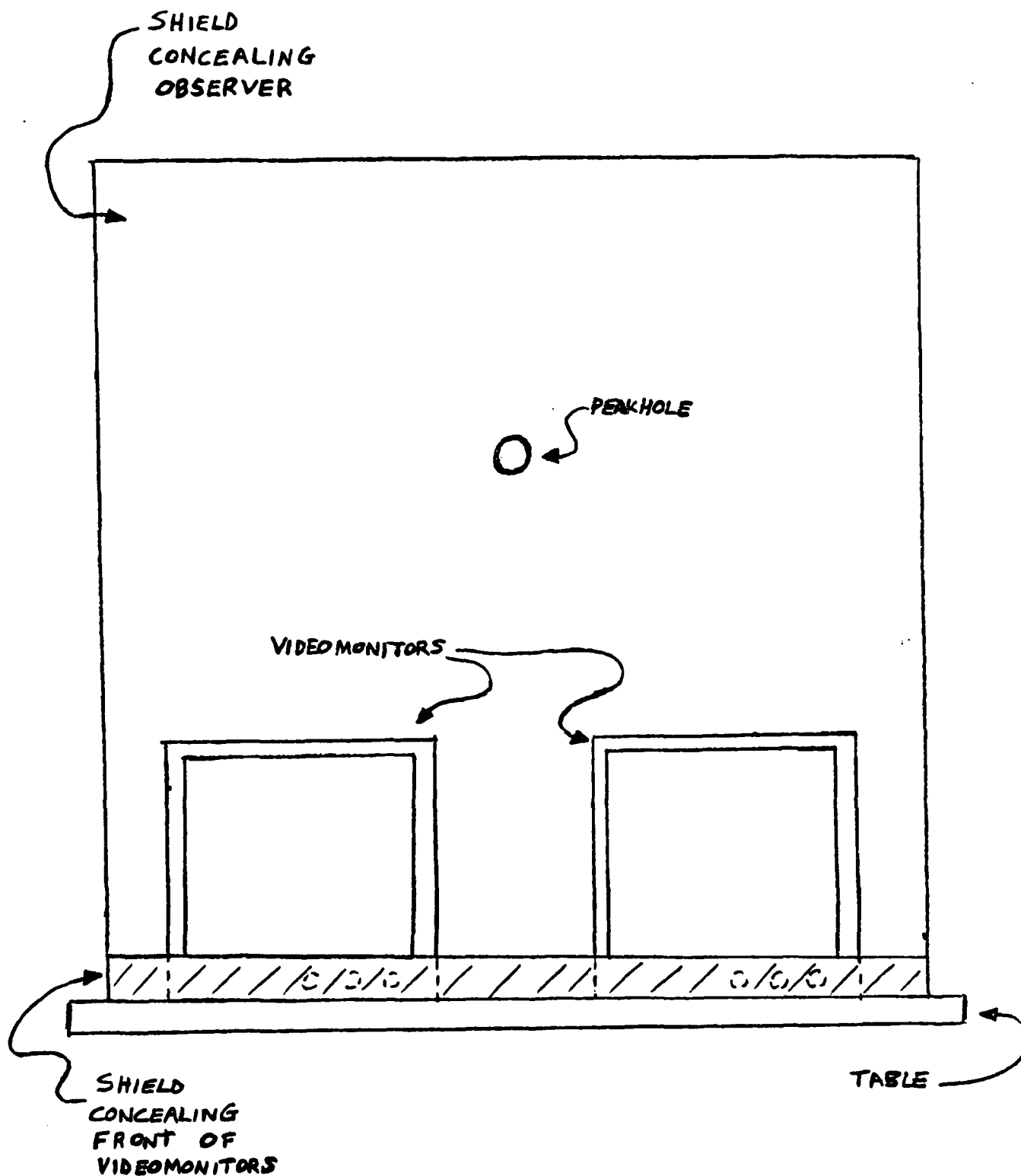


Figure 16. Subject's view of the apparatus used to investigate biological motion in infants.

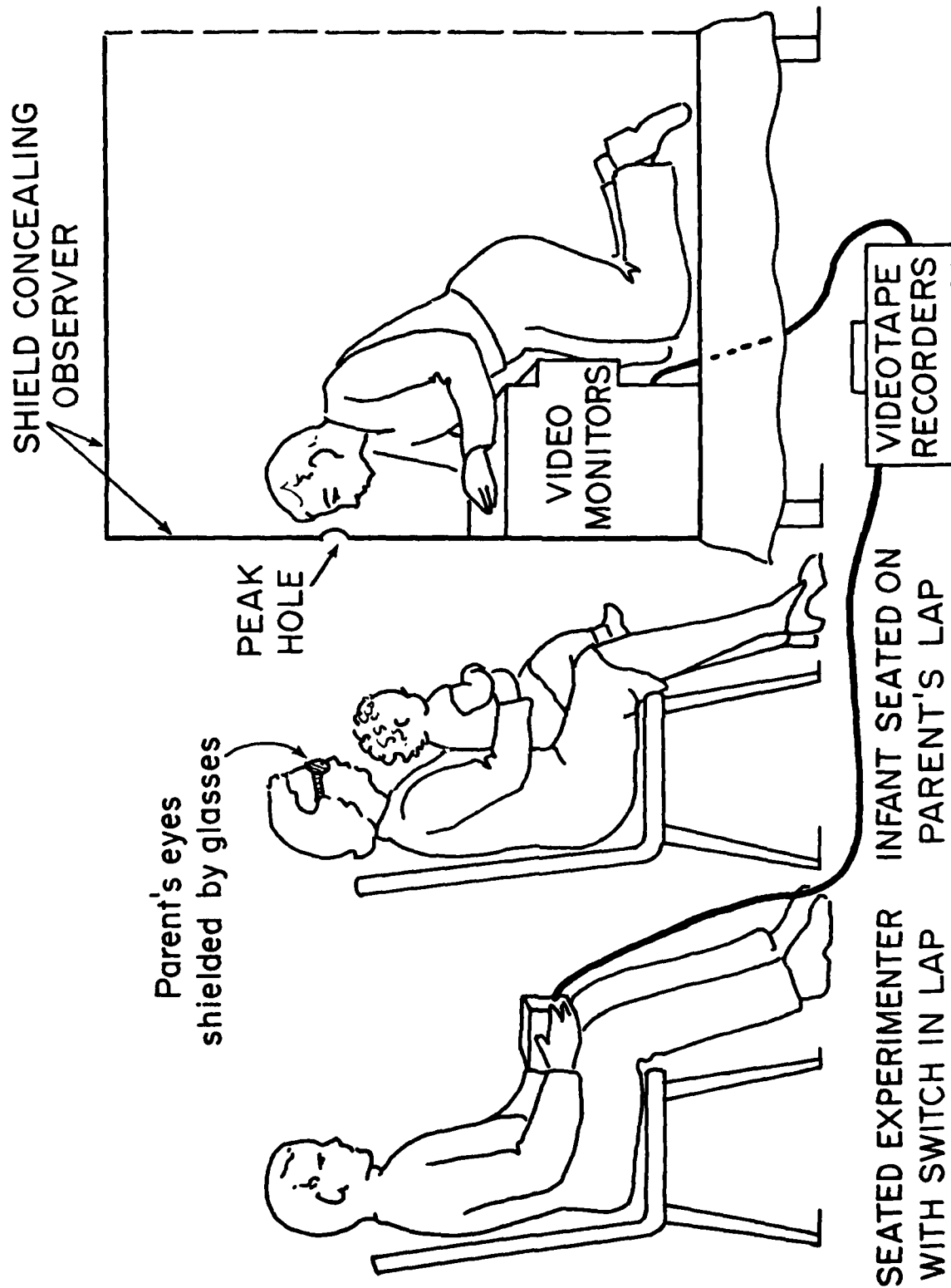


Figure 17. Experimental situation used to implement forced-choice preferential looking technique.

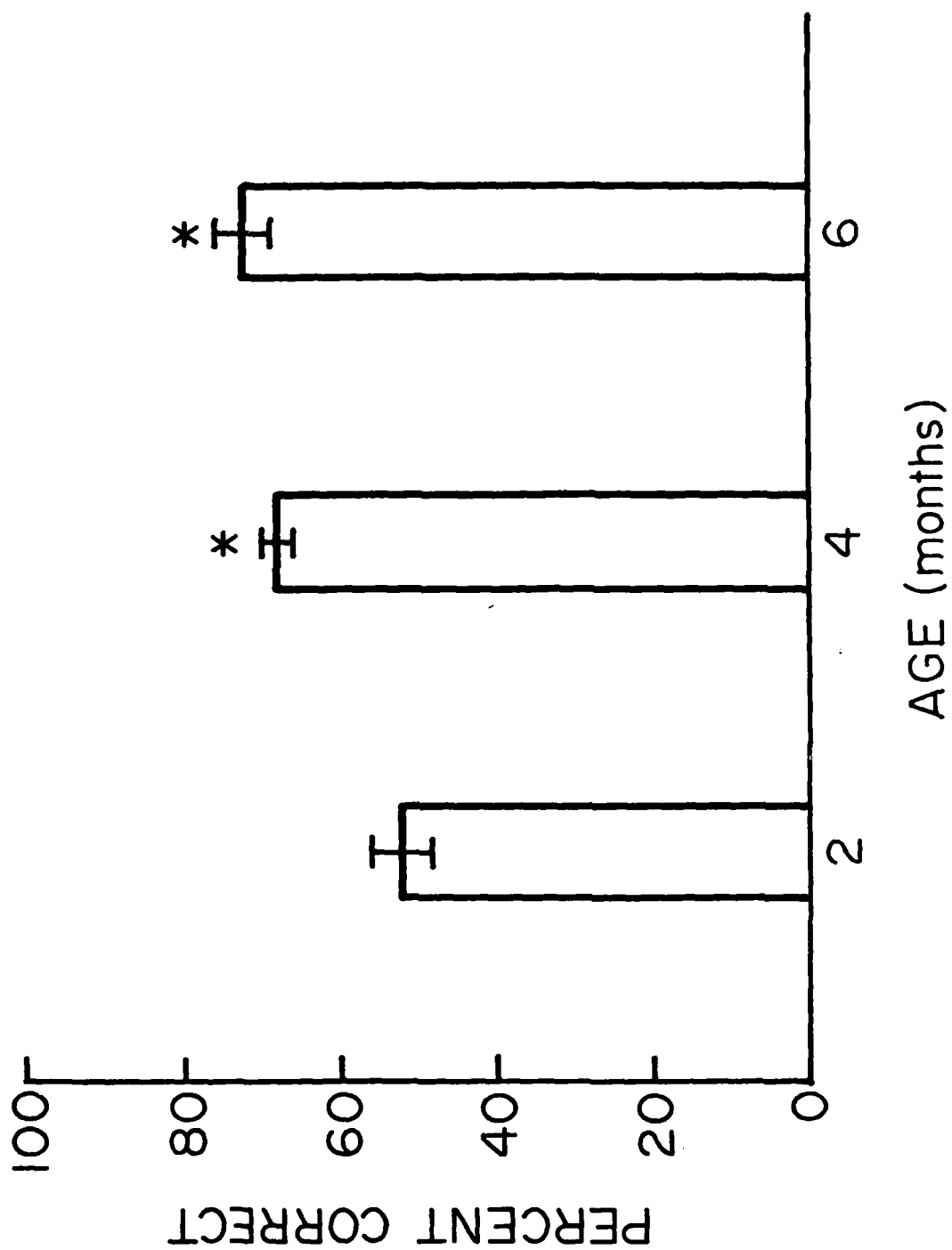


Figure 18. Percent correct as a function of age when upright runner (target) is paired with randomly moving dots (foil). Asterisk indicates significance at the .001 level.

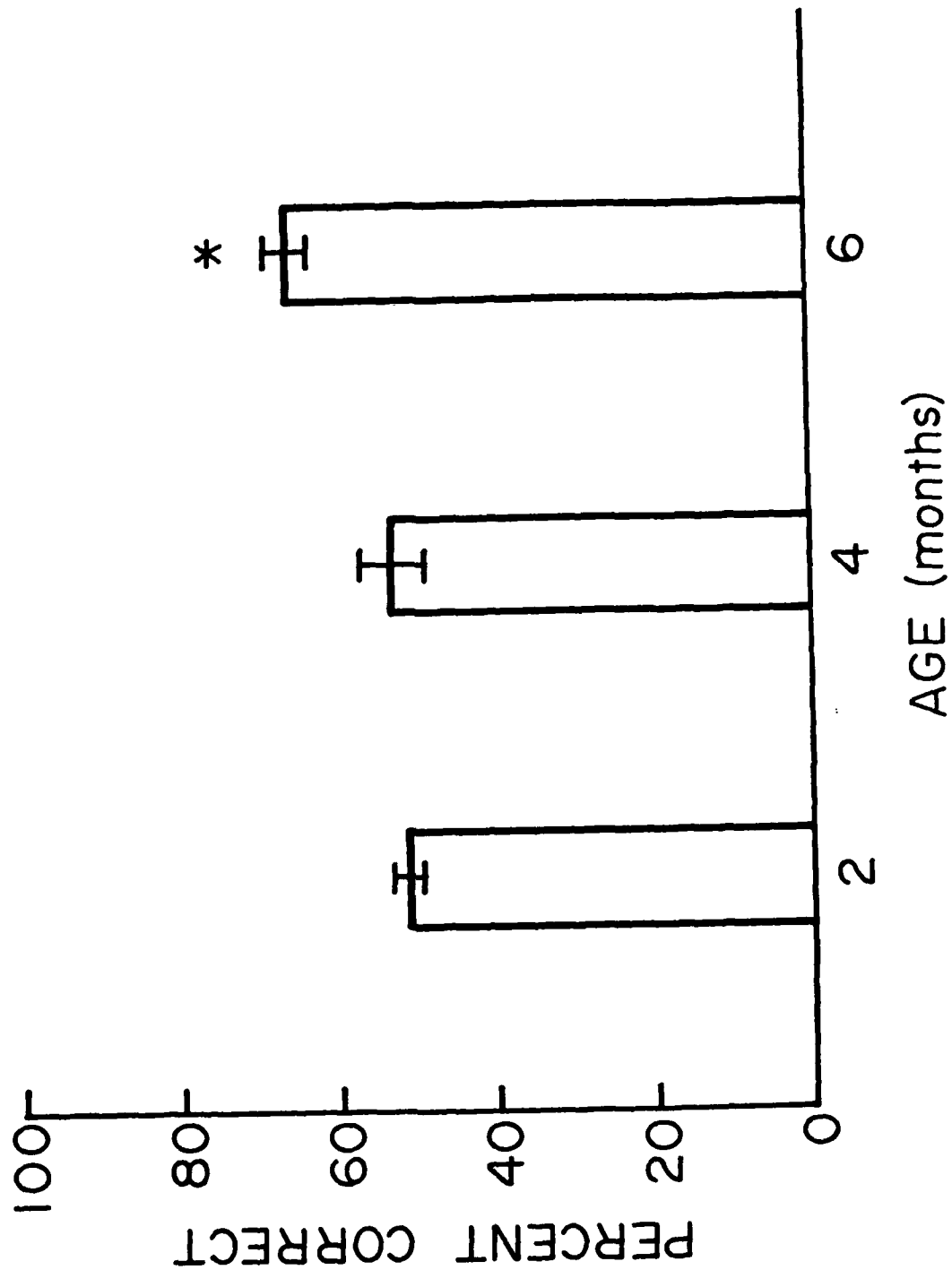


Figure 19. Percent correct as a function of age when upright runner (target) is paired with inverted runner (foil). Asterisk indicates significance at the .02 level.

significantly from chance, while the 6-month-old infants displayed a significant preference. Presumably the difference between the results of this experiment and the previous one reflect the greater similarity between target and foil. In Figure 20 the results of a third cross-sectional study are given for the case where the target was the motion of the hands and the foil consisted of hands defined by misplaced dots. Here again only the 6-month-old infants displayed a significant preference for the target. Again, the presumption is that the greater similarity between target and foil does not permit the 4-month-old infants to make a significant discrimination.

Taken together these data suggest that sensitivity to biological motion becomes manifest in infants between 4 and 6 months of age with some variation in age of onset being a function of the relative salience of target over foil. This is consistent with the view that sensitivity to biological motion is essentially a hardwired phenomenon that does not have to be acquired through extensive interaction with the environment.

The fact that the capacity for processing three-dimensional information is present in infants is much more compatible with relational views of space perception than it is with the cue theory of space perception. The results do not support an assumption, often associated with cue theory, that cues are analysed by a process requiring considerable learning.

Now by way of summing up, the evidence is consistent with the relational theory and its attendant assumption that information about the spatial position of stimuli is processed quite early within the visual system.

Yet it should be clear that it is very difficult, if not impossible

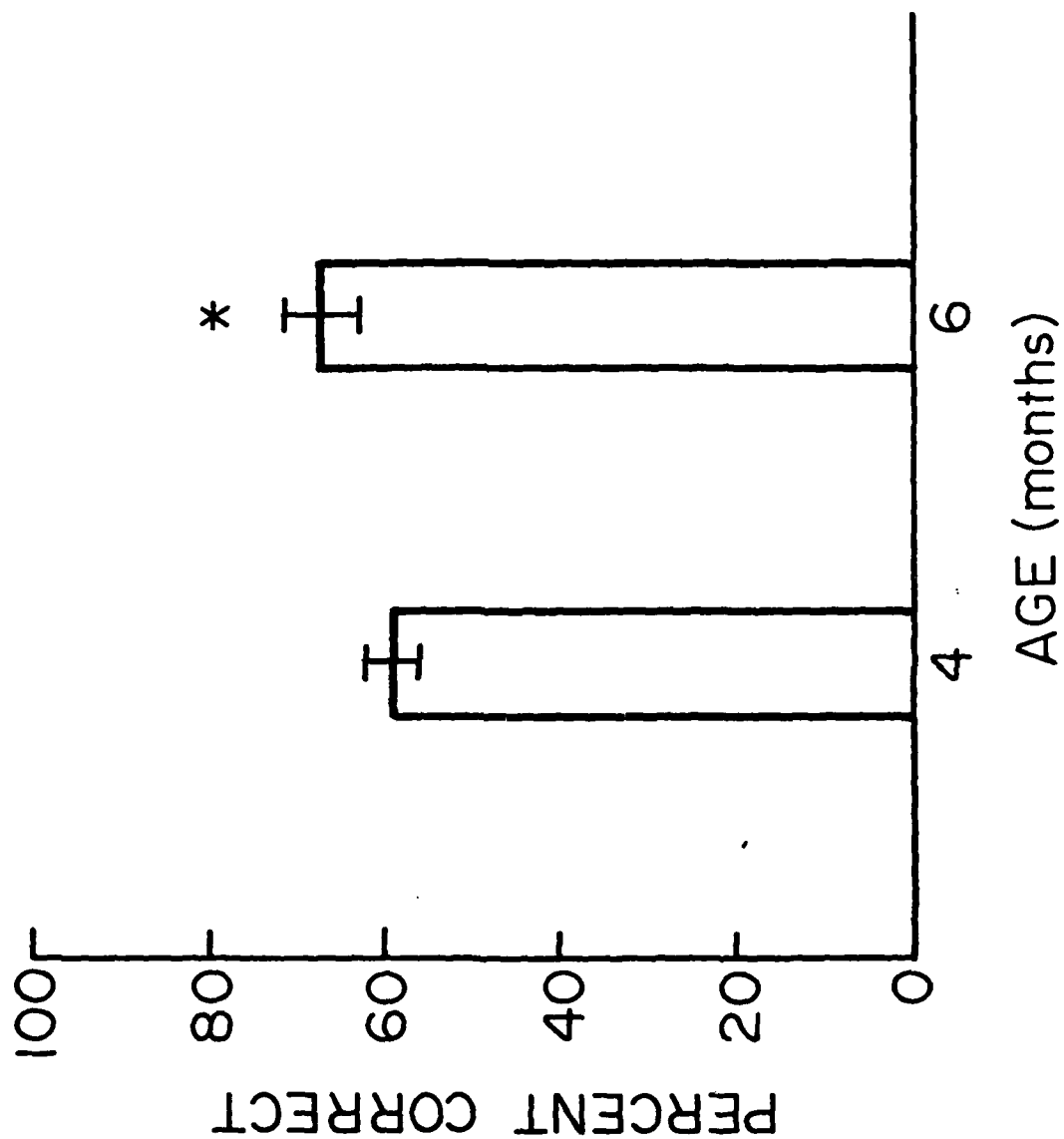


Figure 20. Percent correct as a function of age when motion of hands as conveyed by on-joint dots (target) is paired with motion of hands as conveyed by off-joint dots (foil). Asterisk indicates significance at the .001 level.



to test rigorously hypotheses about the sequence of stages of processing by behavioral methods alone. What looks to be serial by one method can be made parallel by another.

Perhaps the best we can do is to invoke such criteria as parsimony, generality and plausibility, as has been suggested by John Anderson (1976) for the evaluation of cognitive theory. On those grounds relational theory does not fare badly. It seems consistent with the distinction between the two visual systems developed by Herschel Leibowitz (Leibowitz & Post, 1981), Dick Held (1970), and others, where one system, the ambient, is concerned with the location of objects in the world, while the second system, the focal, is concerned with fine-grain analysis of the characteristics of objects. Further, recent evidence for an analogical and spatial representation of visual images seems generally congruent with the assumptions of relational theory. Moreover, recent advances in neurophysiology, which have replaced what was thought to be association cortex with multiple representations of topologically mapped sensory cortical areas, provide no impediment to relational theory.

Indeed the idea that spatial information, including depth position, is represented quite early does not seem implausible. All that is needed is a process that assigns immediately X, Y, and Z coordinate information to all impinging visual stimulation. These initial assignments need not always be correct and could be subject to revision as additional information accrues. It is known, for instance, that even in the absence of stimulation, perception of three-dimensional space persists, and observers confidently, albeit incorrectly, assign depth positions to objects in that perceived space.

But finally, what I find most plausible is that it makes sense that a visual animal designed to survive the volatility of evolutionary pressures would find it adaptive to know quickly the location of objects in space. If I were designing the system, that's the way I would do it.

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